Global Environmental Change 66 (2021) 102200

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Beyond climate, culture and comfort in European preferences for low-carbon heat

Benjamin K. Sovacool [a,b,*], Christina Demski [c], Lance Noel [a]

[a] Science Policy Research Unit (SPRU), School of Business, Management, and Economics, University of Sussex, United Kingdom
[b] Center for Energy Technologies, Department of Business Development and Technology, Aarhus University, Denmark
[c] Centre for Climate Change and Social Transformations, Cardiff University, United Kingdom

ARTICLE INFO

Keywords:
Residential heating
Heat as a service
Heat decarbonization
Cross-national survey
Energy services and practices
Social acceptance of heat

ABSTRACT

It is imperative that climate, energy, and sustainability policy researchers and practitioners grapple with the difficulty of decarbonizing heat, which remains the largest single end-use energy service worldwide. In this study, based on a comparative assessment of five original and representative national surveys in Germany, Italy, Spain, Sweden, and the United Kingdom (N = 10,109), we explore public attitudes of household heat decarbonization in Europe. We explore how people conceive of the purposes of low-carbon heat, their preferences for particular forms of heat supply, and their (at times odd) practices of heat consumption and temperature settings. The data reveal four significant challenges to heat decarbonization that are consistent across geographies: 1) High satisfaction with existing, often fossil fuel based, heating systems; 2) Varying and divergent preferences and expectations for thermal comfort; 3) Householders unlikely to change their heating system in the near-term, in part driven by low familiarity and knowledge of alternative systems; and 4) heat satisfaction appears lower as the fuel mix is decarbonized. The paper concludes by connecting these findings with policy and research implications.

1. Introduction

Heat remains the largest end-use category of energy consumption globally. The International Energy Agency (2020) reports that heating for homes, industry, and commercial applications represents approximately *half* of total final energy consumption around the world. Notwithstanding the sheer importance of heat to most homes and businesses, the IEA also cautions roughly 90% of this heat comes from fossil fuels and high-carbon sources of energy. Even in the European Union, a strong majority of heating and cooling services are met with fossil fuels, where approximately 192.5 million tons of oil equivalent are consumed each year (Sovacool and Martiskainen, 2020).

For reasons such as these, heat has become central in recent discussions of regional and global decarbonization, and its decarbonization is essential to reduce carbon emissions in line with 1.5 to 2 degrees C pathways (Knobloch et al., 2020; Luderer et al., 2018). Within European households, heat remains difficult to decarbonize as well, with one study of carbon footprints in France, Germany, Norway and Sweden noting that heat was the most significant contributor to energy related emissions, far more than those from other services or electricity (Dubois et al., 2019). Underscoring the magnitude of these trends, the International Renewable Energy Agency (IRENA, 2018) calculates in their most recent outlook that between 2015 and 2050, the share of low-carbon electricity in total final energy consumption, including heat, needs to at least double, and that the number of heat pumps in households needs to jump from 20 million to 253 million.

However, despite the well-articulated need to transform heating systems, the literature tends to suggest that it is also one of the most difficult to decarbonize (Wimbadi and Djalante, 2020). Heat remains prone to strong path dependence and lock-in that resists change, with Gross and Hanna (2019: 3) writing that at the national level in Sweden and the United Kingdom, “the development of heating infrastructures can be understood as path-dependent processes, entailing increasing returns to adoption as fuel sources, infrastructures and end-use technologies coevolve.” In Germany, for example, the owners of existing homes reported having far less scope for changing their residential heating system or even preferring low-carbon systems than others such as those building new homes (Michelsen and Madlener, 2012). Heat pumps, a promising option for German heat decarbonization, are perceived by homeowners to be more difficult to get used to and difficult

* Corresponding author at: Science Policy Research Unit (SPRU), University of Sussex, Jubilee Building, Room 367, Falmer, East Sussex BN1 9SL, United Kingdom.
E-mail address: B.Sovacool@sussex.ac.uk (B.K. Sovacool).

https://doi.org/10.1016/j.gloenvcha.2020.102200
Received 3 August 2020; Received in revised form 30 October 2020; Accepted 1 November 2020
Available online 29 December 2020

to maintain properly (Michelsen and Madlener, 2016). Complicating matters, the type of home and features of dwelling are substantial determinants of heating profiles, and regional differences also prevail based on fuel availability as well as climate (Braun, 2010).

The challenge of heat decarbonization is potentially connected to that of renewable electricity integration as well, as it would provide one feasible pathway for incorporating wind and solar energy (Noel et al., 2017; Zarazua de Rubens and Noel, 2019). Moreover, heat services need to not only decarbonize, but also *expand* significantly well into the future, given that heat represents one of the six key "transformations" needed to meet the Sustainable Development Goals (SDGs), but that 2.8 billion households lack adequate access to modern heating and cooking services (Sachs et al., 2019).

A substantial further challenge, and one that we explore in this paper, is that of the interconnected domains of behavior, public engagement and social acceptance (Demski et al., 2015). While there will be different technological solutions and approaches to heat decarbonization in different countries and regions, these will likely include changes in behavior and adopting new low-carbon heating technologies, all the while requiring sweeping changes to the existing heating regime. For example, the UK currently has extremely high penetration of natural gas heating with over 85% of households using a gas boiler (BEIS, 2018), implying a nation-wide switch over to low-carbon systems in the next few decades is necessary if climate change targets are to be met. However, another survey in Ireland found, paradoxically, no evidence that environmental concerns or behaviour affected heating system choices, and also "no clear trend" between a broad range of sociodemographic variables and heating systems (Curtis et al., 2018). Confusingly, in Finland, the opposite was found, with sociodemographic variables identified as significantly affecting different household attitudes towards alternative forms of heating (Ruokamo, 2016). In Sweden, results of an older national survey showed that respondents were highly satisfied with their heating systems, that reliability and cost were the most important determinants of heating choices, and that environmental factors such as climate change were of lower importance (Mahapatra and Gustavsson, 2010). It Italy, households even express a strong preference for wood pellet heating systems rather than fossil fuels or other forms of renewable energy such as solar (Franceschinis et al., 2017). In Spain, existing buildings in Barcelona across a variety of sizes, configurations and community types are shown (due in part to older heating systems) to consume 57% more energy and 28% more peak electricity than needed—creating a promising business market for retrofits, but also underscoring how inefficient the existing housing stock remains (Garriga et al., 2020). Across the European Union as a whole, one older study concluded that "whilst renewable energy adoption is significantly valued by households, this value is not sufficiently large, for the vast majority of households, to cover the higher capital costs of microgeneration energy technologies" (Scarpa and Willis, 2010: 132).

Consequently, we know very little about people's readiness to embrace new low-carbon heating technologies, especially in a year as turbulent as 2020. Indications are that awareness of the need to transition to low-carbon heating is low; in the UK recent research found that 57% of people knew very little about the need to switch away from natural gas for heating (Williams et al., 2018). Because social acceptability will be a key condition for a successful and smooth transition away from fossil fuel based heating, an important starting point is to understand people's current engagement with their existing heating systems, and their perceptions of low-carbon heating.

To address this gap about consumer readiness as well as social acceptability, knowledge, and engagement, we ask: how satisfied are people with existing heating systems, and what expectations to they have regarding their thermal comfort? Might they be resistant to changing their heating system, and how do levels of satisfaction relate to the carbon intensity of a given heating system? To provide answers, we examine self-reported perceptions of heating knowledge, practices, and preferences in five European countries using an extremely recent dataset collected in 2020. These countries were selected because they reflect different winter climates, geographic locations, heating seasons, and distinct energy regimes or markets (Fig. 1), along with different core sociodemographic compositions and energy and climate change data shown in Table 1. We analyze original data from five representative national surveys in Germany (N = 2009), Italy (N = 2039), Spain (N = 2038), Sweden (N = 2023), and the United Kingdom (N = 2000).

By analyzing our country level data as well as our combined sample of 10,109 respondents, we explore people's current satisfaction with existing heating systems, how they conceive of the purposes of low-carbon heat, their preferences for particular forms of heat supply, and their (at times odd) practices of heat consumption. Despite these differences in heating histories, climates, and governance, we find that the challenge of engaging the public with the low-carbon heating is likely to be equally great across all of them. The analysis reveals just how great the challenge of public engagement with low-carbon heating is likely to be, as well as the difficulty of designing corresponding policies and governance architectures for European heat decarbonization.

2. Research design and methods

2.1. Survey instrument

Our survey instrument was designed to take 10–15 min to complete, and it consisted of 23 questions across five sections. The first section explored the socioeconomic and demographic attributes of respondents. The second section investigated heating knowledge and awareness. The third section examined heating practices and dynamics. The fourth section analyzed heating satisfaction and preferences. The fifth section studied heating priorities and business models. Most questions used a 5-point Likert Scale (1 = strongly disagree, 5 = strongly agree), although a final question was open ended, and asked respondents to discuss qualitative interactions with their heating systems. Specific questions used in the analysis for this paper are detailed below.

The survey was offered in English in the United Kingdom, but fully translated into German, Italian, Spanish and Swedish for the other countries, to increase accessibility and completion rates. The survey was implemented online by a market research company, Dynata, using a respondent panel representative of the five European countries (Germany, Italy, Spain, Sweden, and the United Kingdom). Dynata scripted an online version of the survey instrument using their proprietary software. Once checked by the research team, Dynata sent unique person-specific links to the survey to individuals in their respondent panel who have agreed previously to take part in survey research in exchange for incentives. The sampling frame consisted of adults in each of the five countries who had to be over the age of at least 18 years old. The survey was piloted in October-December 2019 and final data collection took place between mid-January to early March 2020. A sample size of roughly 2000 per country was deemed sufficient to fill all quotas based on a combination of age, gender, location, and income. Respondents were selected randomly, and 91% of selected respondents completed the survey. It took an average of 10 min and 30 s for respondents to complete.

A total of 514 respondents were screened out based on quality checks. These quality checks included "flat-liners," straight-line responses on blocks of questions; "rushers," those who gave incomplete, contradictory or unrealistic responses (e.g., the respondent who claimed to have 99 children); and "speeders," those who had unrealistically fast survey completion times. The final sample comprised 10,109 respondents spread across the United Kingdom (N = 2000), Germany (N = 2009), Italy (N = 2039), Spain (N = 2038), and Sweden (N = 2023). Because of the quality checks, note that our final sample includes *complete* response rates, that is each participant answered every question. The final country samples were nationally representative for gender, age, income, and region. See Appendix I for demographic details of the final sample, and Appendix II for the full list of questions posed in the

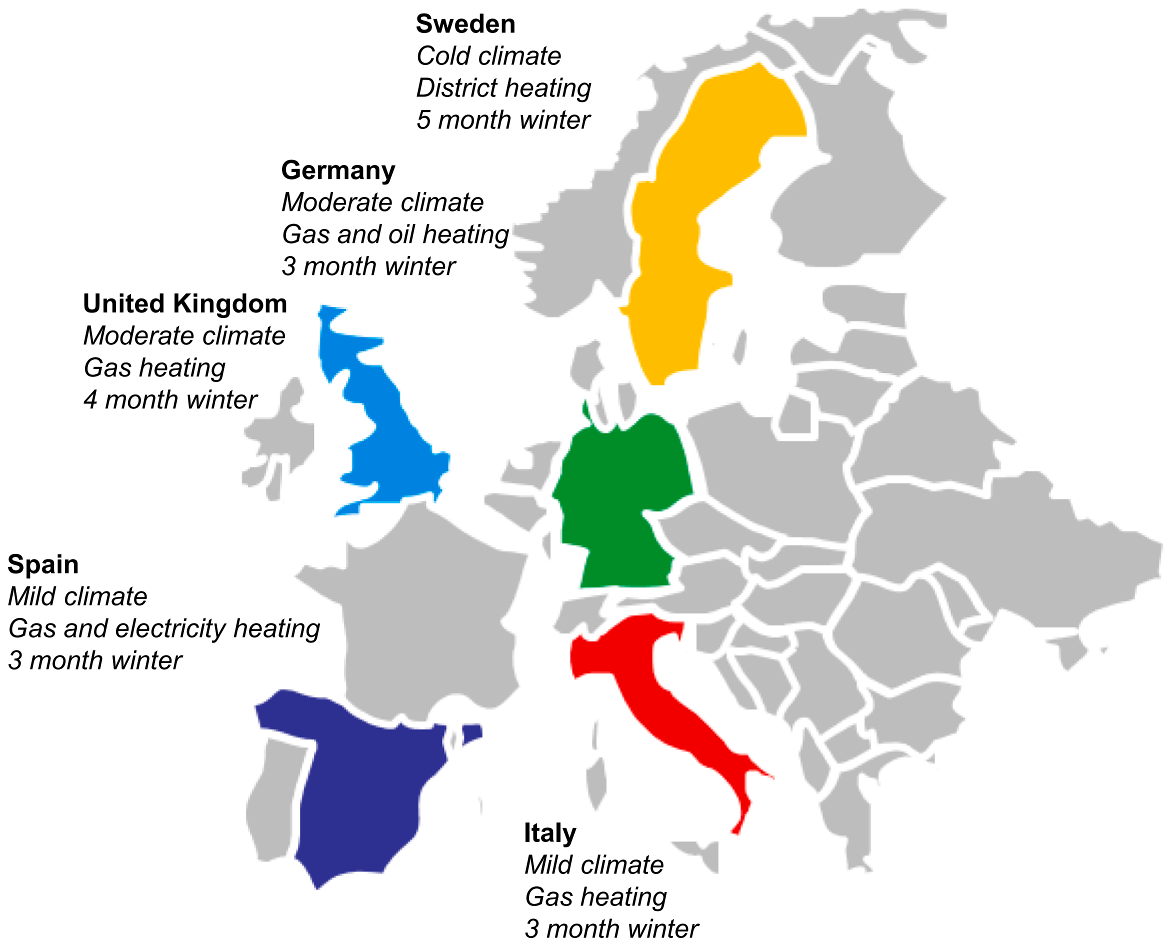

Fig. 1. Overview of five European countries and their energy mixes chosen for our analysis of low-carbon heating. Source: Authors, based on most recent International Energy Agency data.

survey instrument.

2.2. Measures and data analysis

The following measures were used in the analysis as presented in the main article text.

Heat energy literacy: How much would you say you know about how your home and water is heated? A 4-point response scale was used where higher numbers indicate higher literacy: Nothing at all, I have no idea (no heat literacy), I have a vague idea (somewhat literate), I have a good idea (moderate literacy), I have a very good idea (advances literacy or knowledge).

Attention: How much attention do you pay to the amount of heat you use in your home? A 4-point response scale was used where higher numbers indicate more attention: None at all, not very much, a fair amount, a lot.

Satisfaction: How satisfied are you overall with your heating and hot water system? A 5-point response scale was used, where higher numbers indicate higher satisfaction: Very dissatisfied, dissatisfied, neither satisfied nor dissatisfied, satisfied, very satisfied

Winter temperature preference: Thinking about your general temperature setting preferences, how warm should your home be during the winder (in degrees Celsius)? Respondents were required to enter a number between 1 and 40.

Summer temperature preference: How warm (or cool) should your home be during the summer (in degrees Celsius)? Respondents were required to enter a number between 1 and 40.

Likelihood of changing heating source: How likely do you think you will be to change your heat to one of the following sources, if you were given the opportunity, in the next few years? Natural gas/condensing boiler, biomass/bioenergy/wood, heat pump, district heating/heat network, hydrogen, oil/fuel oil/LPG, solar thermal/solar energy, resistive/electric heating. A 5-point response scale was used where higher numbers indicate higher likelihood of changing heating: Very unlikely, somewhat unlikely, neither likely nor unlikely, somewhat likely, very likely. A "don't know" option was also provided.

Interest in emerging business models: Thinking about emerging business models for low-carbon heat, how likely are you to be interested in any of the following? [Note: you may have an answer to this regardless of how much knowledge you have of low carbon heating technologies. However, it is also fine to not know the answer and select "I don't know."]. The following business model ideas were presented to respondents: Heat output as a service (e.g., paying a monthly fee to lease and maintain a heating device, with the provider offering fuel and heat); Heat outcome as a service (e.g., like heat output as a service, but customers are charged for warmth rather than heat), Warmth payment plan (e.g., charging a house for a set number of warm hours per month), Energy payment plans (e.g., bundling a warmth payment plan with other energy services such as electricity or lighting), Asset leasing (e.g., service provider charges a fixed monthly fee to lease the heating appliance, including maintenance and repairs; at the end of the contract, customers can buy out the appliance or have it removed by the provider), Efficient asset leasing (e.g., same as asset leasing, except with some kind of performance guarantee), Low-carbon heating retrofits,

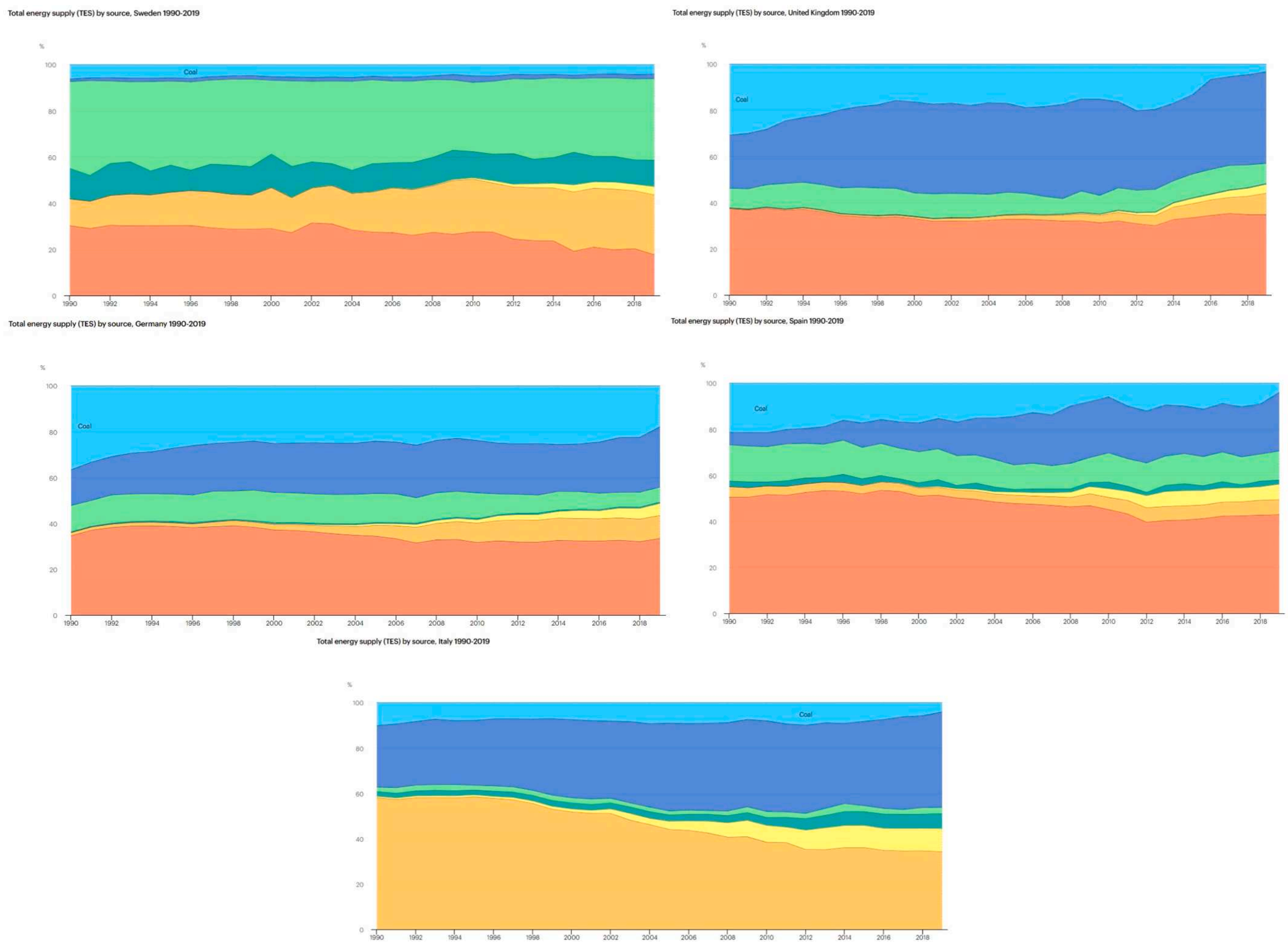

Fig. 1. (*continued*).

Community contracts between neighbors (e.g. peer-to-peer energy trading). A 5-point response scale was used where higher numbers indicate higher likelihood of changing heating: Very unlikely, somewhat unlikely, neither likely nor unlikely, somewhat likely, very likely. A "don't know" option was also provided.

Desired benefits of low-carbon heating: Thinking about the desired benefits of low-carbon heating technologies generally, I believe they should help…[Note: You may have an answer to this regardless of how much knowledge you have of low carbon heating technologies. However, it is also fine to not know the answer and to select "I don't know."] Respondents were shown 11 potential benefits as follows: save time, save money, save energy, save the environment, enhance leisure, provide comfort, improve security, provide care, improve quality of life, increase property values, make life easier. A 5-point response scale was used where higher numbers indicate higher agreement: Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree. A 'don't know' option was also provided.

Analysis: The analysis presented in the main text used the full dataset available for each country. To compare across countries analysis of variance (ANOVA) was used with post hoc follow-up tests using Bonferroni corrections to reduce the risk of Type I error rates.

3. Limitations

Although we believe it has high degrees of validity and rigor, our research design possesses some limitations. First, while our five national country samples are representative terms of gender, age, income, and location, we cannot guarantee representativeness beyond these categories, e.g. household size, education or home ownership. Second, because it is a representative sample, it includes many respondents who may have little awareness or knowledge about heat, and many who may not have actually adopted low-carbon heating innovations. Third, we treat stated preferences as stable and fixed, soliciting them at a single point in time, whereas in reality they are flexible, fluid, and co-constructed over time.

At a more existential level, our reliance on stated preferences and survey techniques to reveal information and knowledge about heating practices and preferences has other weaknesses. Similarly, it may be difficult for people to express a sensible opinion about something they know very little about and haven't thought much about. For instance, people may not be able to report their winter temperature preferences accurately and may struggle to fully understand emerging business models they have never experienced. Respondents may not all have been heating decision makers. Self-reported energy literacy often does not accurately reflect actual literacy - not all respondents will be honest, or know what they don't know. As an example here, stated willingness to switch to low carbon heating systems far exceeds actual uptake in Europe and beyond. These weaknesses can be offset or addressed in future research that validates some of our findings, e.g. thermostat settings in place of reported preferences, designing survey questions to confirm comprehension of new business models, including statistics on actual low carbon heating system uptake alongside stated preferences, and/or drawing from experimental designs that may use "Living Laboratories" where results can be observed rather than inferred.

Table 1
Core sociodemographic, energy and climate change data for our five selected countries.

	Sweden	Germany	United Kingdom	Spain	Italy
Population (millions of people)	10.285	83.132	66.834	47.076	60.297
Gross Domestic Product (GDP, adjusted to purchasing power parity, millions of US$)	574,077	4,659,794	3,255,483	1,987,305	2,664,945
Total primary energy supply (million tons of oil equivalent)	49.77	302.08	175.21	125.02	150.58
Electricity final consumption (Terawatt-hours)	135.64	567.76	325.93	260.14	315.62
Total carbon dioxide emissions (million tons)	34.51	696.13	352.36	248.89	317.14

Source: Authors, based on most recent data from the World Bank and International Energy Agency.

4. Results and Discussion: Four challenges to low-carbon heat

This section presents the results according to our four research questions, organized around the themes of satisfaction (4.1), expectations and preferences (4.2), resistance to change (4.3), and decarbonization (4.4).

4.1. High satisfaction with existing heating systems

Across countries, respondents report having a good idea about their current heating system and paying a fair amount of attention to the heat they use (Table 2). There are small differences across the five sampled countries for literacy ($F(4, 10104) = 131.894$, $p < 0.001$) and attention ($F(4, 10104) = 442.629$, $p < 0.001$) with Sweden reporting lowest literacy and attention levels followed by Germany, Spain and then the UK. Italian respondents report the highest levels of literacy and attention.

Nevertheless, this finding challenges the expectation that we would have seen more divergence across geographic settings—especially given that they house different energy markets, heating regimes, winter seasons, actors and cultures. One meta-survey of smart energy systems across Europe even noted that heating and cooling practices vary considerably based on embodied knowledge, as well as socially shared

Table 2
Mean self-reported knowledge (heat energy literacy) and attention paid to existing heat systems across five European countries (standard deviations in brackets).*

	Heat energy literacy (self-reported)[a]	Attention[a]
Italy	3.14 (0.69)	3.33 (0.61)
United Kingdom	2.98 (0.84)	3.13 (0.71)
Spain	2.90 (0.85)	3.03 (0.76)
Germany	2.77 (0.81)	2.94 (0.75)
Sweden	2.58 (0.94)	2.41 (0.84)

*Higher numbers indicate higher literacy and attention.
[a] All country differences significant at $p < 0.05$ or 0.01 levels after Bonferroni corrections are applied.

conventions and habits of heating (Mela et al., 2018). Our findings suggest the opposite, that heat literacy and self-reported knowledge varies little across different cultures and countries (and remain low to moderate on a five point scale).

With regards to satisfaction with existing heating systems we find almost no differences across countries - respondents generally report being satisfied ($F(4,10104) = 21.268$, $p < 0.001$). Only respondents from Sweden are slightly less satisfied ($p < 0.001$). This finding suggests that despite differences in geographic locations, climates, heating systems and cultures, people in these European countries are broadly happy with the way they are currently heating their homes; in fact, less than 10% of the populations report dissatisfaction. This is in line with research that shows that, while people do report problems with other thermal comfort aspects such as draughts and damp, generally this does not translate to dissatisfaction with their heating system (Energy Technologies Institute 2018). This suggests that people are not aware of possible improvements in thermal comfort (Schweiker et al. 2019) experiences that low-carbon energy systems may provide.

4.2. Expectations of thermal comfort

Many plans for heat decarbonization include reductions for energy used to heat homes. Improving the thermal performance of buildings is likely to play a large part in reducing demand, but there are also expectations that people change their heating practices to reduce demand, for example by only heating (or cooling) rooms that are in use or putting on extra clothing (Grubler et al., 2018; Van Vuuren et al., 2018). However, current trends appear to be in the opposite direction, that is, towards harnessing the power of heating and cooling technologies to alter indoor climates, rather than altering behavior or wearing more climate friendly clothing; for example, UK homes are thought to be 4 degrees C warmer now than in 1970 (Eyre and Killip, 2019).

In order to calculate the difference between mean preferred thermostat setting in winter and summer, mean winter and summer temperatures were determined using publicly available data from the World Health Organization. Using June through August as summer months and December through February as winter months, mean monthly temperature were determined by country over the last five years of available data (2011–2016). The resulting seasonal means were then subtracted from the preferred thermostat temperatures, as shown in Table 3.

To gauge people's temperature expectations, we asked survey respondents their preferred home temperatures during the winter and summer (in degrees Celsius). Table 4 presents mean preferred temperatures broken down by country. Due to large variability, we also present data as median and modal temperatures. Surprisingly, survey respondents in all five countries had higher temperature preferences in the winter than the summer. In some countries this difference was quite small (e.g. Italy), whereas for others it different by quite a few degrees (e.g. United Kingdom).

Winter temperature preferences appear to be between 20 and 21

Table 3
Seasonal Mean Temperature by Country, and Difference compared to thermostat temperature. All temperatures in degrees Celsius.

Country	Season	Mean Temperature	Mean Pref. Thermostat Setting	Difference
Germany	Summer	17.85	19.78	+1.93
	Winter	1.97	21.28	+19.3
Italy	Summer	21.22	20.73	−0.49
	Winter	5.23	21.03	+15.8
Spain	Summer	22.23	20.87	−1.36
	Winter	6.84	21.83	+14.99
Sweden	Summer	13.18	19.17	+5.99
	Winter	−7.12	21.00	+28.12
United Kingdom	Summer	14.37	16.56	+2.19
	Winter	4.46	20.88	+16.42

Table 4
Winter and summer temperature preferences in five European countries.

	Preferred WINTER temperature (in degrees Celsius)	Preferred SUMMER temperature (in degrees Celsius)
Sweden	Mean = 21.00 (3.39)	Mean = 19.17 (4.02)
	Median = 21	Median = 20
	Mode = 20	Mode = 20
	Diff = +28.12	Diff = +5.99
Germany	Mean = 21.28 (2.76)	Mean = 19.78 (4.23)
	Median = 21	Median = 20
	Mode = 20	Mode = 20
	Diff = +19.3	Diff = +1.93
Italy	Mean = 21.03 (3.46)	Mean = 20.73 (5.18)
	Median = 20	Median = 20
	Mode = 20	Mode = 20
	Diff = +15.8	Diff = -0.49
Spain	Mean = 21.83 (3.25)	Mean = 20.87 (4.35)
	Median = 22	Median = 21
	Mode = 20	Mode = 20
	Diff = +14.99	Diff = −1.36
UK	Mean = 20.88 (4.80)	Mean = 16.56 (5.97)
	Median = 20	Median = 17
	Mode = 20	Mode = 18
	Diff = +16.42	Diff = +2.19

degrees, with Spain reporting the highest average preferred temperature. Summer temperature preferences are lower between 19 and 20 degrees; the UK appears to be an outliner in this respect with preferred temperatures of 17–18 degrees.

These findings suggest that people's temperature preferences do not only represent technical sufficiency insofar as they prevent people from freezing to death, but may also be influenced by other factors, such as a need or desire for higher temperatures as a possible respite from cold external temperatures in the winter and hot weather in the summer. As such, temperature preferences may be more representative of an "ideal" temperature, rather than some minimum threshold of basic comfort. The preferred lower summer temperatures in the UK in particular suggest that this may increase cooling demand in the coming decades as average summer temperatures are projected to increase. For example, the UK Met Office (2018) estimates that summer temperatures could increase by 5.4 degreesC by 2070.

Comparing the preferred temperatures to actual average winter and summer temperatures indicated by "Diff" in Table 3, with data from the World Health Organization (2020), it is evident that respondents from Sweden expect the most from their heating/cooling systems. However, their expected temperatures are not largely different from other countries (e.g. around the 20 to 21 degrees for the winter) suggesting that independent of climate, people in these European countries have a similar understanding of what is considered a preferred or acceptable level of comfort (in terms of temperature setting). It also means that Sweden has the highest need/expectation for heating, which may explain why their satisfaction levels are slightly reduced compared to the other countries. One explanation could be that the Swedes may prefer higher temperatures because it's colder in Sweden. Thermal comfort is influenced by radiant heat and air flow as well as air temperature. If it's colder in Sweden, there may be less radiant heat and more drafts, so they may find higher air temperatures are needed to feel the same level as comfort as in a place with a warmer climate.

These findings also indicate that heating demand is unlikely to reduce in the future. Policies that encourage people to actively reduce the temperature to which they heat (and cool) their homes may have limited efficacy in the context of these findings. Indeed, if these findings represent "ideal" preferences it is even possible that people's expectations are not currently being met, which opens up the possibility of substantial rebound effects (Sorrell et al., 2020), for example, as the thermal performance of buildings improves through energy efficiency improvements. Overall, people across our five sampled countries appear to have a preference for quite warm homes in the winter and cool homes in the summer. This borders on being patently obvious: people prefer higher temperatures to warm them up when the weather is cold, and lower ones to cool them down when the weather is hot. For the same reasons why people have hot drinks on cold days, and ice-cubes in their drinks on hot days, low-carbon heating systems should fit within consumer expectations of using heating and cooling systems as sources of comfort. It is unlikely that this preference will change rapidly in the future, which also suggests that temperature settings may be inelastic as prices increase, or affordability decreases.

4.3. People resistant to changing their heating systems

High satisfaction with existing heating systems (see 4.1) suggests people are not currently considering switching to alternative systems. To explore this in more depth, we asked survey respondents how likely it is that they will change their heating to a new source/system in the next few years if given the opportunity. They were asked to indicate their likelihood of switching for a mixture of potentially low-carbon and fossil fuel based sources. While there are small differences across countries (Table 5), the general finding is clear: people are unlikely to change to a new system in the next few years (Table 6). This is in line with other findings that suggest people are unlikely to change their heating systems unless it needs to be replaced (DECC 2013).

An additional point about Table 5 deserves mentioning. Another way to interpret these data is that households do not necessarily care about the heating system they end up with. Previous research shows that people care a lot more about the quality of their heating experiences (e.g. how warm and comfortable they can get, how convenient this is, what it costs), than which type of heating system or source of energy delivers the comfort (Mallaband and Lipson, 2020; Sovacool et al., 2020). Indeed, as shown by the case of Sweden discussed below, households may only care beyond the quality of their heat when something goes wrong, e.g. potentially monopolistic implementation of heating districts.

Low-carbon systems did not attract higher ratings. In fact, with the exception of solar, natural gas received the highest likeliness-to-adopt ratings of all the heat sources. This may be, in part, because natural gas is currently widely used across Europe and therefore quite familiar to people. This trend is also evident in the individual countries with the exception of Sweden where heat pumps (M = 3.13, s.d. = 1.43) were preferred more than natural gas (M = 3.83, s.d. = 1.42, $t(1407) = 15.300$, $p < 0.001$). This is in line with Sweden having 5 to 11 times more heat pump sales per capita than the other four countries in recent decades (Hannah et al., 2016).

Low familiarity is another reason why people may be unwilling to change to a new heating system, especially when combined with high satisfaction with their existing systems. A relatively high number of survey respondents (18–23% across countries) chose the "don't know" response option indicating a lack of knowledge and familiarity with many of these technologies. A similar percentage of respondents chose the middle option on the response scale ("neither likely nor unlikely"), which could also indicate uncertainty. The findings are mirrored in another set of questions asking people about their interests in a number of new business models for delivering heat services. This includes business models such as energy as a service or peer-to-peer trading. Tellingly, responses to these questions also indicate high levels of uncertainty (See Table 7). These combined findings are important because research has shown that high levels of unfamiliarity can increase risk perceptions (Slovic et al., 1980) and thus reduce the likely engagement with a new technology or service. Low awareness and high unfamiliarity are important barriers to overcome if new, low-carbon heating systems are to be rolled out on a widespread scale.

When asked specifically about the desirability of a number of possible benefits of low-carbon heating technologies, the highest agreement in all countries was found for "saving the environment". Other potential benefits that received general agreement across

Table 5
Likeliness to adopt alternative heating systems, with added information on country differences for each technology. All post hoc tests were performed with Bonferroni corrections. Please note that there may be a large number of differences that are significantly different ($p < 0.05$) but this is likely due to very large sample sizes. The actual difference/effect is very small in most cases. Means (and standard deviations) are shown from a five-point response scale from very likely (1) to very unlikely (5).

	UK	Germ-any	Italy	Spain	Sweden	Note on differences across countries
Natural Gas	3.06	3.49	2.67	2.98	3.82	$F(4,8325) = 165.383$, $p < 0.001$.
	(1.37)	(1.45)	(1.33)	(1.48)	(1.42)	All differences significant except between Spain and UK.
Biomass	3.87	3.88	3.42	3.70	3.74	$F(4,8211) = 36.208$, $p < 0.001$.
	(1.21)	(1.27)	(1.26)	(1.30)	(1.37)	All differences significant except between UK/Germany and Sweden/Spain.
Heat pump	3.78	3.69	3.21	3.57	3.13	$F(4,8163) = 79.158$, $p < 0.001$.
	(1.23)	(1.34)	(1.25)	(1.27)	(1.43)	All differences significant except between UK/Germany, Germany/Spain and Italy/Sweden.
District heating	3.91	3.74	3.48	3.76	3.29	$F(4,8083) = 57.387$, $p < 0.001$.
	(1.19)	(1.38)	(1.23)	(1.26)	(1.49)	All differences significant except between Germany and Spain.
Hydrogen	3.96	4.00	3.51	3.91	3.92	$F(4,7821) = 60.983$, $p < 0.001$.
	(1.19)	(1.22)	(1.23)	(1.20)	(1.35)	Italy significantly different to all others. No other significant differences.
Oil	4.10	4.04	3.86	3.96	3.97	$F(4,8182) = 8.247$, $p < 0.001$.
	(1.18)	(1.26)	(1.26)	(1.25)	(1.39)	Significant differences between UK/Spain, UK/Italy and Germany/Italy. No other significantly differences.
Solar	3.46	3.35	2.72	2.97	2.98	$F(4,8521) = 82.041$, $p < 0.001$.
	(1.34)	(1.44)	(1.37)	(1.40)	(1.43)	All differences significant except UK/Germany and Spain/Sweden.
Resistive electric	3.85	4.05	3.50	3.45	3.75	$F(4,8186) = 63.112$, $p < 0.001$.
	(1.21)	(1.19)	(1.23)	(1.32)	(1.40)	All differences significant except UK/Sweden and Italy/Spain

countries include saving money and energy, providing comfort, improve quality of life, increase property values and making life easier (Fig. 2). Benefits such as saving time, enhancing leisure, and improving security received more mixed responses. Again, while there are small country differences, there is consistency in the types of benefits people expect from low-carbon heating technologies.

Furthermore, the self-stated results here conflict with actions as revealed in other parts of the survey. For example, here the respondents claim that “enhancing leisure” was of low importance, but above it is argued that there are high expectations of thermal comfort. Similarly, despite the fact that “save the environment” was the highest agreement, it was still natural gas that was the most likely to be adopted next in many of the countries. This contradiction is further underlined by the discussion in the next section, which shows that low-carbon heating regimes do not necessarily guarantee high levels of satisfaction. In short, respondents profess to highly value environmental protection for future heating systems, but this does not (yet) meaningfully translate into changed heating practices or readiness to adopt low-carbon heating systems. As such, it may be that low-carbon heating may not diffuse until it provides more luxury than the current systems, or benefits from government intervention (Noel et al., 2017b).

4.4. *Decarbonization and lower carbon intensities may be less socially acceptable*

One concerning trend is that the country with the highest decarbonized level of heating (Sweden) also has the lowest satisfaction levels (Fig. 3). This strongly implies we need to invest in improving low carbon heating systems as they do not appear to deliver satisfactory experiences to households at the moment. Reasons for lower satisfaction levels in Sweden are likely to be multifaceted; they could for example be related to the technology mix or the policies governing heating regimes. With regards to technologies, Sweden has mostly achieved decarbonization by expansion of heat pumps and low-carbon heating in district heating networks. These technologies cover over 60% of heating needs for our Swedish respondents, with resistive heating making up the next highest proportion (15%). This is markedly different to the technology mix in the other four European countries, where natural gas makes up the largest proportion (see Fig. 3). If satisfaction levels vary by technology, this could be a reason for lower satisfaction levels in Sweden.

Indeed, there are significant differences in heat satisfaction when comparing technology types owned by respondents ($F(8, 10100) = 37.241$, $p < 0.001$), even when accounting for the fact that most systems provide integrated heating and hot water. Expounding the concern, the many forms of decarbonization add statistically significant *dis*satisfaction, including resistive heating ($p < 0.001$), district heating ($p < 0.001$), hydrogen ($p = 0.02$), and heat pumps ($p = 0.05$). Nonetheless, the technology with highest satisfaction rate is solar thermal, showing that heat satisfaction is not solely dependent on carbon intensity. Discouragingly, natural gas attracts one of the highest satisfaction levels across countries.

The lower satisfaction levels of decarbonized heat energy like district heating may also be due to backlash on how they were implemented, and not intrinsic to the technology itself. Sweden, for example, has had a history of consumer distrust of district heating operators, fearing they would be taken advantage of when acting as a natural monopoly (Magnusson, 2016). The Swedish heat regime is largely operated by incumbent firms who offer few alternatives to district heat and who tend not to invest in efficiency or other efforts of consumer empowerment (Dzebo and Nykvist, 2017). Its transition to biomass based energy was largely steered from the top-down, by government actors (Lucia, 2014). It is also a heat market populated by many international firms (such as E. ON, Fortrun and Vattenfall) with mergers and acquisitions to increase the profitability of heat supply, but not necessarily user satisfaction.

Given heating satisfaction is dependent on local contexts and technology type, policies incentivizing the transition to decarbonized energy sources must be flexible and allow consumers to make their own choice. One option is to further disincentivize carbon-intense heating sources using a carbon tax, which can provide stability and economic support to all decarbonized heating technologies. At the same time, lack of explicit support for a particular technology may put planning-intensive technologies (i.e. district heating) at a disadvantage, further decreasing heating satisfaction. Considering overall low public engagement with heating systems, a comprehensive government plan would be necessary, particularly one that focuses on *how* a decarbonization transition would be implemented (e.g., information and education, public engagement, a focus on procedural justice, carbon taxes), as opposed to *what* (e.g., a focus on the benefits and barriers of a specific heating technology).

5. Conclusion

Decarbonization of heat remains one of the main challenges for reaching climate change targets in Europe. Heat decarbonization has large implications for households both in terms of changes to heating practices and technologies. We also know that an engaged populace will make the transition smoother and faster, but social acceptability is likely to be one of the greatest challenges in this sector, unlike for example, in electricity generation where changes happen away from households and

Table 6
How likely do you think you will be to change your heat to one of the following sources, if you were given the opportunity, in the next few years? Means (and standard deviations) are shown from a five-point response scale from very likely (1) to very unlikely (5).

	Natural gas	Biomass	Heat pump	DH	Hydrogen	Oil	Solar	Electric
UK	3.06 (1.37)	3.87 (1.21)	3.78 (1.23)	3.91 (1.19)	3.96 (1.19)	4.10 (1.18)	3.46 (1.34)	3.85 (1.21)
Germany	3.49 (1.45)	3.88 (1.27)	3.69 (1.34)	3.74 (1.38)	4.00 (1.22)	4.04 (1.26)	3.35 (1.44)	4.05 (1.19)
Italy	2.67(1.33)	3.42 (1.26)	3.21 (1.25)	3.48 (1.23)	3.51 (1.23)	3.86 (1.26)	2.72 (1.37)	3.50 (1.23)
Spain	2.98(1.48)	3.70 (1.30)	3.57 (1.27)	3.76 (1.26)	3.91 (1.20)	3.96 (1.25)	2.97 (1.40)	3.45 (1.32)
Sweden	3.82(1.42)	3.74 (1.37)	3.13 (1.43)	3.29 (1.49)	3.92 (1.35)	3.97 (1.39)	2.98 (1.43)	3.75 (1.40)
Mean across countries	3.18 (1.46)	3.72 (1.29)	3.48 (1.33)	3.64 (1.32)	3.86 (1.25)	3.98 (1.27)	3.09 (1.42)	3.71 (1.29)
Don't know	18%	19%	19%	20%	23%	19%	16%	19%
Neither likely nor unlikely	21%	19%	22%	19%	18%	15%	19%	20%

Table 7
Percentage of respondents likely or unlikely to consider a number of innovative business models to deliver heating services. See Section 2 for exact wording of question and descriptions of services. Note the high percentage of respondents choosing the "don't know"or middle response of "neither likely nor unlikely" indicating a lack of knowledge and high levels of uncertainty.

	Very likely	Somewhat likely	**Neither likely or unlikely**	Somewhat unlikely	Very unlikely	**Don't know**
Heat output as a service	7.3%	15.7%	**25.0%**	15.7%	18.9%	**17.5%**
Heat outcomes as a service	5.1%	15.3%	**27.3%**	17.8%	15.9%	**18.5%**
Warmth payment plans	6.0%	13.9%	**24.9%**	18.7%	20.8%	**15.7%**
Energy payment plans	6.5%	17.9%	**27.1%**	16.7%	15.9%	**15.8%**
Asset leasing	5.3%	13.6%	**25.7%**	18.3%	20.1%	**17.1%**
Efficient asset leasing	5.0%	13.1%	**26.4%**	18.2%	19.3%	**18.1%**
Low-carbon heating retrofits	7.4%	18.1%	**26.4%**	15.7%	15.0%	**17.4%**
Community contracts between neighbors	5.9%	12.5%	**26.2%**	17.3%	20.8%	**17.4%**

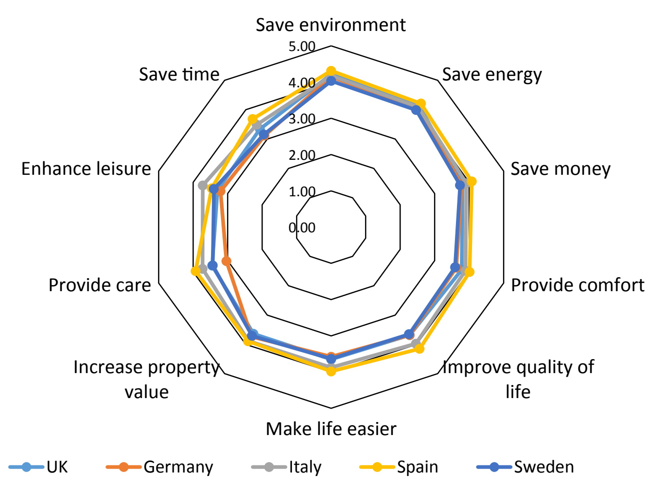

Fig. 2. Benefits expected from low-carbon heating technologies by survey respondents in five European countries (higher numbers mean more agreement that benefit is important).

have less implications for individuals. Using a survey in five European countries with a sample of n = 10,109, here we expose four such challenges with public engagement and acceptance in particular.

First, across our full sample, people expressed high satisfaction with their existing heating systems despite reporting only basic to moderate levels of heating literacy. This reveals a conundrum as people are implying they are satisfied with remaining less literate (or not fully literate). Our respondents also strongly support natural gas as a fuel across all of the countries, at the same time they profess to want to save the environment. Or, consumers may not even realize that socio-technical systems such as gas central heating cause or contribute to climate change (Energy Systems Catapult, 2020). In a nutshell: consumers are largely happy with what they have, or believe their existing fossil-fueled heating systems are environmentally benign, divorcing them from participating in heat energy discussions and as a result, are uninformed. At the same time, if policymakers are relying on decarbonization (or even electrification) of heating sources, it is absolutely necessary for consumers to be included and aware. But there are currently few incentives for them to be made aware.

Second, households reported high levels of desired thermal comfort, both in the summer and in the winter. These high expectations make it difficult to promote sustainable options which may not be designed to provide such a level of thermal comfort, and can also lead to possible rebounds if or when these households switch to more efficient or more cost-effective forms of low-carbon heating. Put another way: people may demand thermal comfort that is independent of its price. These high expectations may imply that improvements made by energy efficiency measures may be subject to large rebound effects. However, they also point the way towards particular perceptions and attitudes about heat that will need met if consumers are to be appeased. Put in very simple terms: It will be significantly easier to decarbonize heat if we design solutions that give consumers the heat they want, than if we rely on consumers putting up with less heat than they would like. There could even be luxury aspects in consumer demand, whereby some classes of consumers will not accept "technically sufficient" low carbon technologies. It may do well to further innovate and change heating systems to meet these embedded expectations of users, rather than trying to change the embedded behaviors of the users to adapt to more rigid heating systems (or narrower ranges of thermal comfort). Rather than chastise or shame users for these expectations, researchers, firms, and innovators should further develop low-carbon innovations that meet them.

Third, we find that households are unlikely to switch to low-carbon heating, particularly in the near-term, a problem worsened with high degrees of uncertainty and lack of knowledge. This holds true regardless of the respondents' country location of a respondent (country-level effects were small), which does suggest that geographic location is not necessarily an important determinant of heating satisfaction and preferences. Put another way: all five countries face the challenges that we set out above. Surprisingly, respondents both rate the importance of "saving the environment" but also favor low-carbon options such as district heating the least, and natural gas remains the most preferred source of heat across the entire sample. This would offer some policy support for taxing carbon, as opposed to supporting specific heating technologies. Other innovative policy options could be mandatory phasedowns or restrictions on gas boilers—a boiler ban similar to the emerging bans on petrol/diesel vehicles (Plötz et al., 2019). Another

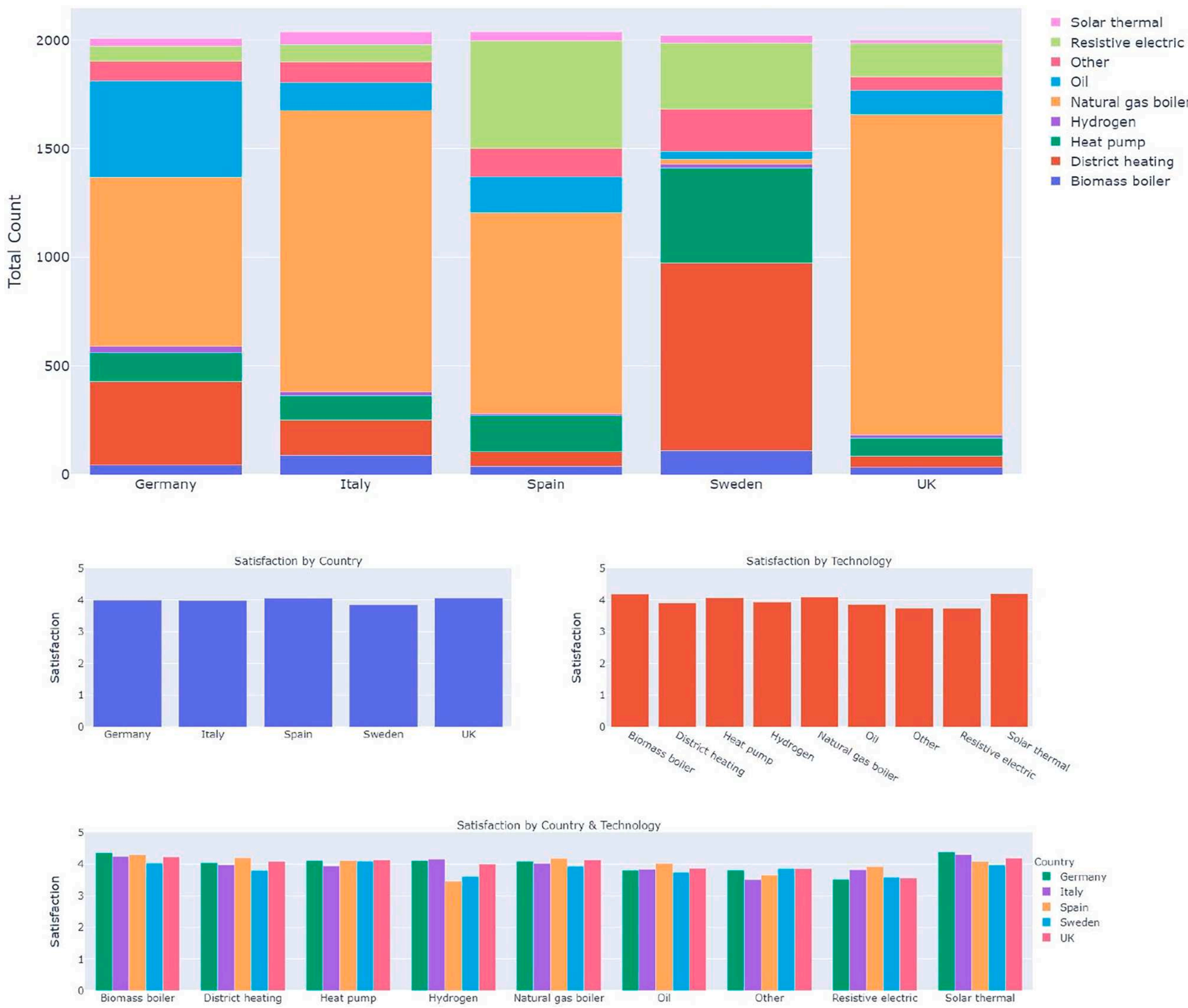

Fig. 3. Existing heating supply (top panel) and heating satisfaction levels by technology and country (bottom panel) (Count).

option could be to have an allowance or permit based policy such as a carbon certificate for the home (similar to the MOT testing and inspection for automobiles in the UK) where annual emissions are measured and have to be reduced over time to avoid fines.

Fourth, higher decarbonization levels may possibly lead to lower satisfaction levels, if not implemented correctly. One country-level effect we did explore in more detail was the lower satisfaction ratings given by respondents in Sweden, which seem to be less about the technology *per se* and more about how it is governed, how the monopolistic market functions, and how users have control (or not) over temperatures, although this would not explain any resistance or opposition to heat pumps. One implication here is that mandating a switch to low-carbon heating technology may have big impact on overall heat satisfaction in the long-term, even if it is done in a fair manner and issues of governance are addressed (that is, people tend not to associate low-carbon heat with satisfaction regardless of which of the five countries we examined). This finding also relates to our one above about expectations of thermal comfort, offering evidence that low carbon heating systems are currently failing to deliver the heat experiences consumers desire.

Although we cover a mix of different European countries, and believe our findings are generalizable to other countries and regions of the world, as they face similar challenges, our insights are most relevant first and foremost to the five countries examined. That said, countries with lower income levels or at lower levels of economic development can still benefit from our findings, especially as these are the regions of the world that are set to see the greatest increase in the adoption of technologies intended to provide thermal comfort, notably solar thermal systems (e.g., China, see Sovacool and Martiskainen, 2020) or air conditioning (e.g., India, see Osunmuyiwa et al., 2020, or China, see Zhang et al., 2020, or the Middle East and North Africa, see Velders et al., 2015). Here, the core aspects of our findings—low to moderate knowledge and literacy, differing expectations, resistance to change, and lower satisfaction with environmentally friendly innovations—could translate into possible challenges facing *all* new cooling or heating systems.

Ultimately, we find that the public in these European countries are not currently poised to engage seriously with the heat decarbonization challenge, whether that is changing to alternative technologies or reducing their thermal consumption. This is probably, in part, fueled by a lack of engagement and knowledge on the issue combined with existing high satisfaction levels with their current heating systems. Serious policy interventions may be warranted to change this status quo. Our findings suggest that heating decarbonization will likely not be delivered by existing energy markets or by voluntary actions on behalf of households.

Further research on this theme may want to look at why are people satisfied with their existing heating systems and how this may pose opportunities or challenges for decarbonization of heating. For example, those with natural gas heating tend to particularly like the immediacy of gas heating systems (quick delivery of heat) as well as the experience of radiant heat (hot radiators) (Energy Technologies Institute, 2018). Research may need to explore how households or incumbent heat suppliers can be incentivized, or even forced, to decarbonize. Given it is likely people will resist heat decarbonization if not convinced that expected thermal comfort levels and benefits can be achieved (or perhaps exceeded), as well as low levels of public knowledge of heating systems, future decarbonization effort may face opposition due to misinformation and myths (Noel et al., 2019), as well as bad experiences. As such, a key government policy based on our findings is to develop information campaigns and increase public engagement with their heating systems. Additionally, governments should consider increasing carbon taxes on heating energy, as this would be a technology-neutral way to incentivize decarbonization, and would likely increase the public's engagement and understanding of the importance of the heating sector to climate goals, alongside innovative options such as banning boilers or implementing home heating inspection schemes. If such holistic policy mixes were to emerge, they could catalyze heating innovations that remedy may of the shortcomings identified here, including content with existing heating, expectations of thermal comfort, reluctance to change, and declining satisfaction with decarbonization.

CRediT authorship contribution statement

Benjamin K. Sovacool: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - original draft. **Christina Demski:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft. **Lance Noel:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions (CREDS), grant reference number EP/R035288/1, the Centre for Climate Change and Social Transformations (CAST), grant reference number ES/S012257/1, and the UK Energy Research Centre (UKERC), grant reference number EP/S029575/1. This paper has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 764025. The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

References

BEIS (2018). Clean Growth – Transforming Heating. Overview of current evidence. London: UK.

Braun, F.G., 2010. Determinants of households' space heating type: a discrete choice analysis for German households. Energy Policy 38 (10), 5493–5503.

Curtis, J., McCoy, D., Aravena, C., 2018. Heating system upgrades: The role of knowledge, socio-demographics, building attributes and energy infrastructure. Energy Policy 120, 183–196. https://doi.org/10.1016/j.enpol.2018.05.036.

DECC (2013). Homeowner's Willingness To Take Up More Efficient Heating Systems. Research report by Ipsos MORI and the Energy Saving Trust. London: Department of Energy and Climate Change. Available at: https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge.

Demski, C., et al., 2015. Public values for energy system change. Global Environ. Change 34, 59–69. https://doi.org/10.1016/j.gloenvcha.2015.06.014.

Di Lucia, Lorenzo, Karin Ericsson, Low-carbon district heating in Sweden – Examining a successful energy transition, Energy Research & Social Science, Volume 4, December 2014, Pages 10-20.

Dubois, G., et al., 2019. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. Energy Res. Social Sci. 52, 144–158.

Dzebo, A., Nykvist, B., 2017. A new regime and then what? Cracks and tensions in the socio-technical regime of the Swedish heat energy system. Energy Res. Soc. Sci. 29, 113–122.

Energy Systems Catapult. 2020. Understanding Net Zero: A Consumer Perspective. April 17.

Energy Technologies Institute, 2018. How can people get the heat they want at home, without the carbon? Available at: https://www.eti.co.uk/insights.

Eyre, N., Killip, G. (Eds.), 2019. Shifting the focus: energy demand in a net-zero carbon UK. Centre for Research into Energy Demand Solutions. Oxford, UK.

Franceschinis, C., Thiene, M., Scarpa, R., Rose, J., Moretto, M., Cavalli, R., 2017. Adoption of renewable heating systems: an empirical test of the diffusion of innovation theory. Energy 125, 313–326. https://doi.org/10.1016/j.energy.2017.02.060.

Garriga, S., Martínez, M., Dabbagh, M., 2020. Krarti, Optimal carbon-neutral retrofit of residential communities in Barcelona, Spain. Energy Build. 208, 109651.

Gross, R., Hanna, R., 2019. Path dependency in provision of domestic heating. Nat. Energy 4, 358–364. https://doi.org/10.1038/s41560-019-0383-5.

Grubler, A., et al., 2018. A low energy demand scenario for meeting 1.5C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527.

Hannah, R., Parrish, B., Gross, R., 2016. Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply. UKERC Technology and Policy Assessment working paper. UK Energy Research Centre, London.

International Energy Agency, 2020. Heating. Available at. https://www.iea.org/fuels-and-technologies/heating.

IRENA, 2018. Global Energy Transformation: A Roadmap to 2050. International Renewable Energy Agency, Abu Dhabi.

Knobloch, F., Hanssen, S., Lam, A., et al., 2020. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat. Sustain. https://doi.org/10.1038/s41893-020-0488-7.

Luderer, G., Vrontisi, Z., Bertram, C., et al., 2018. Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Clim. Change 8, 626–633. https://doi.org/10.1038/s41558-018-0198-6.

Magnusson, D., 2016. Who brings the heat? – From municipal to diversified ownership in the Swedish district heating market post-liberalization. Energy Res. Social Sci. 22, 198–209.

Mahapatra, K., Gustavsson, L., 2010. Adoption of innovative heating systems - needs and attitudes of Swedish homeowners. Energy Effi. 3, 1–18.

Mallaband, B., Lipson, M., 2020. From health to harmony: Uncovering the range of heating needs in British households. Energy Res. Social Sci. 69, 101590.

Mela, H., et al., 2018. Framing smart meter feedback in relation to practice theory. Sustainability 10, 3553. https://doi.org/10.3390/su10103553.

Michelsen, C. C., & Madlener, R. (2012). Homeowners' preferences for adopting innovative residential heating systems: A discrete choice analysis for Germany. Energy Economics, 34(5), 1271-1283. doi://doi.org/10.1016/j.eneco.2012.06.009.

Michelsen, C.C., Madlener, R., 2016. Switching from fossil fuels to renewables in residential heating systems: an empirical study of homeowners' decisions in Germany. Energy Policy 89, 95–105.

Noel, L:. et al. "Cost minimization of generation, storage and new loads, comparing costs with and without externalities." Applied Energy 189, 110-121 (2017). https://doi.org/10.1016/j.apenergy.2016.12.060.

Noel, L, BK Sovacool, J Kester, GZ de Rubens. 2017b. "Conspicuous diffusion: Theorizing how status drives innovation in electric mobility" (2017) Environmental Innovation and Societal Transitions 31, 154-169.

Noel, L, GZ de Rubens, BK Sovacool, J Kester . "Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety" (2019) Energy research & social science 48, 96-107.

Osunmuyiwa, Olufolahan O., Sarah R. Payne, P. Vigneswara Ilavarasan, Andrew D. Peacock, David P. Jenkins, I cannot live without air conditioning! The role of identity, values and situational factors on cooling consumption patterns in India, Energy Research & Social Science, Volume 69, 2020, 101634.

Plötz, P., Axsen, J., Funke, S.A., et al., 2019. Designing car bans for sustainable transportation. Nat. Sustain. 2, 534–536. https://doi.org/10.1038/s41893-019-0328-9.

Ruokamo, E., 2016. Household preferences of hybrid home heating systems - a choice experiment application. Energy Policy 95, 224–237.

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., et al., 2019. Six transformations to achieve the sustainable development goals. Nat. Sustain. 2, 805–814. https://doi.org/10.1038/s41893-019-0352-9.

Scarpa, R., Willis, K., 2010. Willingness-to-pay for renewable energy: primary and discretionary choice of British households' for micro-generation technologies. Energy Econ. 32 (1), 129–136. https://doi.org/10.1016/j.eneco.2009.06.004.

Schweiker, M., Abdul-Zahra, A., André, M., et al., 2019. The Scales Project, a cross-national dataset on the interpretation of thermal perception scales. Sci. Data 6, 289. https://doi.org/10.1038/s41597-019-0272-6.

Slovic, P., Fischhoff, B., Lichtenstein, S., 1980. Facts and fears: understanding perceived risk. In: Schwing, R.C., Alberts, W.A. (Eds.), Societal Risk Assessment: How Safe is Safe Enough? Plenum Press, New York.

Sorrell, S., Gatersleben, B., Druckman, A., 2020. The limits of energy sufficiency: a review of the evidence for rebound effects and negative spillover from behavioural change. Energy Res. Social Sci. 64, 101439.
Sovacool, Benjamin K., Martiskainen, Mari, 2020. Hot transformations: Governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom. Energy Policy 139, 111330.
Sovacool, B.K., Osborn, J., Martiskainen, M., Lipson, M., 2020. Testing smarter control and feedback with users: Time, temperature and space in household heating preferences and practices in a Living Laboratory. Global Environmental Change 65 (102185), 1–13.
UK Met Office (2018) UK Climate Projections https://www.metoffice.gov.uk/news/releases/2018/ukcp18-launch-pr.
Van Vuuren, D., et al., 2018. Alternative pathways to the 1.5C target reduce the need for negative emission technologies. Nat. Clim. Change 8, 391–397.
Velders, Guus J.M., et al., 2015. Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmos. Environ. 123, 200–209.
Wimbadi, Ramanditya Wimbardana, Djalante, Riyanti, May 2020. From decarbonization to low carbon development and transition: a systematic literature review of the conceptualization of moving toward net-zero carbon dioxide emission (1995–2019). J. Cleaner Prod. 256 (20), 120307.
Williams, H., Lohmann, T., Foster, S., Morrell, G., 2018. Public acceptability of the use of hydrogen for heating and cooking in the home. Results from qualitative and quantitative research in UK. Madano, London.
World Health Organization. Climate Change Knowledge Portal: Download Data. https://climateknowledgeportal.worldbank.org/download-data. Accessed May 2020.
Zarazua de Rubens, G., Noel, L., 2019. The non-technical barriers to large scale electricity networks: analysing the case for the US and EU supergrids. Energy Policy 135, 1111018. https://doi.org/10.1016/j.enpol.2019.111018.
Zhang, Xiao-Bing, Sun, Jiayu, Fei, Yinxin, Wei, Chu, 2020. Cooler rooms on a hotter planet? Household coping strategies, climate change, and air conditioning usage in rural China. Energy Res. Social Science 68, 101605.